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Study of $\Lambda n$ FSI with $\Lambda$ quasi-free productions on the $^3\text{H}(e, e' K^+)X$ reaction at JLab


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Abstract. An \(nn\Lambda\) is a neutral baryon system with no charge. The study of the pure \(\Lambda n\) system such as \(nn\Lambda\) gives us information on the \(\Lambda n\) interaction. The \(nn\Lambda\) search experiment (E12-17-003) was performed at JLab Hall A in 2018. In this article, the \(\Lambda n\) FSI was investigated by a shape analysis of the \(^3\)H\((e,e'K^+X)\) missing mass spectrum, and a preliminary result for the \(\Lambda n\) FSI study is given.

1 Introduction

In the nucleon-nucleon \((NN)\) interaction, realistic nuclear potentials have been constructed based on rich \(NN\) scattering data. On the other hand, there are relatively large uncertainties due to limited \(\Lambda N\) scattering data in case of the \(\Lambda N\) interaction. In addition, since there is no \(\Lambda n\) scattering data, the \(\Lambda n\) interaction have been established from the limited \(\Lambda p\) scattering data assuming charge symmetry (CS). However, it has been experimentally observed that charge symmetry is broken between \(A=4\) mirror \(\Lambda\) hypernuclei \((^4_\Lambda\text{H}, ^4_\Lambda\text{He})\) [1]. Therefore, it is important to derive the \(\Lambda n\) interaction experimentally. One of the major experimental investigation methods for the \(\Lambda N\) interaction is the study of the \(\Lambda N\) final state interaction (FSI).

The FSI is the reaction between the recoil \(\Lambda\) and a nucleon in a nucleus, and it is known to make an enhanced structure in the missing mass spectrum [2, 3]. Therefore, the spectroscopic study of a pure \(\Lambda\)-neutron system such as \(nn\Lambda\) is expected to give us information on the \(\Lambda n\) interaction. The \(^3\)H\((e,e'K^+X)\) missing mass spectrum was obtained by using two HRS spectrometers and a tritium target \((^3\text{H})\) which is a radioactive material in 2018 at Jefferson Lab (JLab) Hall A [4, 5]. In this study, the \(\Lambda n\) FSI interaction was investigated by analyzing the \(^3\)H\((e,e'K^+X)\) missing mass spectrum obtained by this experiment (E12-17-003).

2 \(^3\)H\((e,e'K^+X)\) missing mass spectrum

In this experiment, a cryogenic tritium gas target \((40 \text{ K})\) with a thickness of 84.8 mg/cm\(^2\) was irradiated with an electron with an energy \((E_e)\) of 4.3 GeV, and measured momenta of scattered electrons \((p_{e'} = 2.2 \text{ GeV/c})\) and \(K^+\) mesons \((p_K = 1.8 \text{ GeV/c})\) by two high resolution spectrometers (HRS). The missing mass \((M_X)\) was calculated with the momentum vectors \((\vec{p}_{e'}, \vec{p}_K)\) and energies \((E_{e'}, E_K)\) as follows:

\[
M_X = \sqrt{(E_e + m_T - E_{e'} - E_K)^2 - (\vec{p}_{e'} - \vec{p}_e - \vec{p}_K)^2}.
\]  (1)

where \(m_T\) and \(\vec{p}_e\) are the mass of tritium and momentum vector of the electron beam, respectively. As a function of the measured the \(^3\)H\((e,e'K^+)X\) missing mass, the missing mass
spectrum is shown by black dots with error bars in Fig. 1. This vertical axis represents the differential cross section for the $^3$H($e, e'K^+)$X reaction. Any parameter values such as momentum acceptances ($d\Omega_{e'}, d\Omega_K$) used to calculate the cross section are explained in Ref. [6].

2.1 Monte Carlo Simulation (SIMC)

The solid black line in Fig. 1 shows the $\Lambda$ quasi-free ($\Lambda$-QF) distribution calculated by the Monte Carlo Simulation (SIMC); SIMC is a JLab standard Monte Carlo simulation code, which takes into account the effects such as the proton Fermi momentum, kaon decay. Comparing the SIMC spectrum with the missing mass spectrum, the region over 60 MeV is good agreement. However, there is some enhancement around $nn\Lambda$ mass threshold ($−B_\Lambda ≈ 0$ MeV) and 20 MeV regions. Around the $nn\Lambda$ mass threshold where a $nn\Lambda$ peak is expected to exist, there are excess events which cannot reproduced by SIMC.

Figure 1. $^3$H($e, e'K^+)$X missing mass spectrum. The horizontal and vertical axes indicate the binding energy of the $\Lambda$(MeV) and the differential cross section of the missing mass (nb/sr/2 MeV), respectively. The black points with bar shows the experimental data. The black solid line is the simulation result (SIMC) of the $\Lambda$-QF distribution without any final state interaction effects.

3 Calculation of the $\Lambda n$ final state interaction (FSI)

The cross section for $\Lambda$-QF productions including FSI is written as follows:

$$\left(\frac{d\sigma}{d\Omega}\right)_{FSI} = I(\vec{k}_{\Lambda n})\left(\frac{d\sigma}{d\Omega}\right)_{w/o FSI},$$  \hskip 1cm (2)

where $I(\vec{k}_{\Lambda n})$ is the influence factor depending on a relative momentum ($\vec{k}_{\Lambda n}$) between a neutron in tritium and a recoil $\Lambda$. In the two-body ($\Lambda-n$) scattering model, the influence factor can be written by using the Jost function ($J$) as $I(\vec{k}_{\Lambda n}) = 1/|J(\vec{k}_{\Lambda n})|^2$ [8]. Moreover, in the effective range approximation ($k_{\Lambda n} \cot \delta = -1/a + r/2k_{\Lambda n}^2$), the Jost function is written as:

$$J(\vec{k}_{\Lambda n}) = \frac{k_{\Lambda n} - i\beta}{k_{\Lambda n} - i\alpha},$$  \hskip 1cm (3)

$$\frac{1}{2}r(\alpha - \beta) = 1, \quad \frac{r}{2}a\beta = -\frac{1}{a},$$  \hskip 1cm (4)

where $a$ and $r$ are a scattering length and an effective range, respectively. Figure 2 shows the calculation results of the influence factor with various $\Lambda n$ potential models. The weighting ratio of the spin singlet ($^1S_0$) and triplet ($^3S_1$) factors is one to three. From Eq. (2)-(4), the cross section of the $\Lambda$-QF productions including $\Lambda n$ FSI can be obtained.
4 Results

4.1 Λn potential model dependence

The Λn FSI effect was estimated by the $\chi^2$ fitting of the $^3$He($e,e'K^+$)$X$ missing mass spectrum. The structure around $nnΛ$ mass threshold ($-B_Λ \sim 0$ MeV) exists, which could not be reproduced by the SIMC spectrum. Therefore, this structure was described as background by using the Breit-Wigner function ($f_{WB}$) because it was successful to reproduce well by using this function in Ref.[6]. The fitting function of the $^3$He($e,e'K^+$)$X$ missing mass spectrum was defined as:

$$\left(\frac{d\sigma}{d\Omega}\right)_{FSI} = w_{FSI} \cdot I_{ΛΛΛ}(\vec{k}_{ΛΛΛ}) \left(\frac{d\sigma}{d\Omega}\right)_{SIMC} + w_{WB} \cdot f_{WB},$$

where $w_{FSI}$ and $w_{WB}$ are scaling factors for the SIMC spectrum and Breit-Wigner function, respectively. These weighting factors were scaled by the $\chi^2$-fitting with the missing mass spectrum within a range from 0 to 60 MeV. The fitting results of the SIMC spectrum by each Λn FSI model are shown in Fig. 3.

4.2 Search for the best Λn FSI parameters

The scattering length ($a$) and effective range ($r$) are parameters that determine the characteristics of the Λn potential. Since these parameters ($a, r$) were used for calculation of the Λn FSI in Eq.(3)-(4), they can be evaluated by the $\chi^2$-fitting of the experimental spectrum. Figure 4 shows the $\chi^2$-distribution depending on average Λn scattering length ($\bar{a} = (a_s + 3a_t)/4$) and effective range ($\bar{r} = (r_s + 3r_t)/4$). As a result, $\chi^2$ values had the minimum value at ($\bar{a}, \bar{r}$) = (−2.6, 5.0) fm. Each colored marker in Fig. 4 shows a value of ($a, r$) in the Λn potential model. Moreover, regions hatched in red show the experimental results of the singlet and triplet values for Λp FSI [3]. Since the potential values of Λn FSI (−2.6, 5.0 fm) took values between these of Λp FSI of the spin singlet and triplet, the potential values at (−2.6, 5.0) fm does not conflict with a result of the Λp FSI. On the other hand, the black solid, dashed and dashed-dot lines in Fig. 4 show the contour lines added one, two and three from the chi-square minimum ($\chi^2_{min} = 59$). Especially, the contour line at $\chi^2 = 1$ represents the statistics error, so when the scattering length ($a$) is -2.6 fm, the effective range ($r$) is successfully limited to be $3.8 < r < 6.3$ fm (preliminary).
Figure 4. The $\chi^2$ distribution depending on an average scattering length ($\bar{a}$) and effective range ($\bar{r}$). The average values are assumed to be the same value of spin singlet and triplet. The $\chi^2$ has its minimum value at $(-2.6, 5.0)$ fm (star marker in pink). The colored markers show the potential value in each $\Lambda n$ potential model. The hatched boxes in red show an experimental result of the $\Lambda p$ FSI in the singlet and triplet, respectively [3]. The black lines show the contour lines at $\chi^2 = 60, 61, 62$.

5 Summary

The search for the $nn\Lambda$ experiment (E12-17-003) was performed at JLab Hall A in 2018. By analyzing the $^3$H($e, e'K^+$)X missing mass spectrum by the $\chi^2$-fitting, the $\Lambda n$ FSI was investigated in this study. As a result, the effective range ($r$) was successfully given a limit for a certain scattering length ($a$) from Fig. 4 (preliminary).

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